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Laboratory Experiment

Thirst for a Solution: Alginate Biopolymer Experiments for the Middle and High School Classroom

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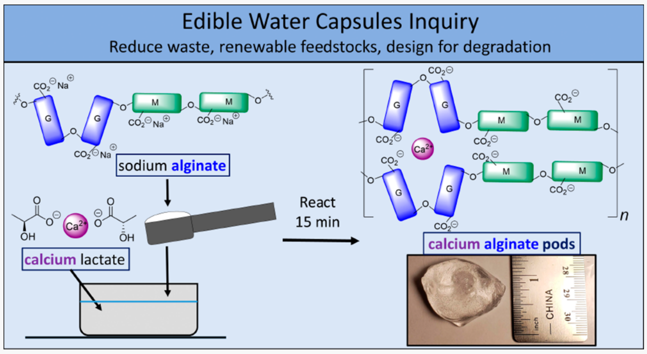
ABSTRACT: Comprehensive curricula are described for middle and high school classrooms built around the synthesis of biodegradable calcium alginate capsules prepared from food-safe chemicals. Experiments and activities question whether calcium alginate capsules are a viable alternative to single-use water bottles and consider what characteristics are required to become commercially successful. Students prepare calcium alginate capsules using sodium alginate and calcium lactate and observe the physical properties of the fluid-filled pod. In the high school curriculum, capsules using alternative group 2 cation salts are made and compared qualitatively to the calcium alginate capsules. After exploring the capsules, students work collaboratively to design an inquiry experiment. The high school curriculum offers extensions such as analyzing a related literature article and creating professional research posters on their inquiry experiments. The middle school curriculum includes a scaffolded introduction on the topics of renewable vs nonrenewable resources and introduces simple polymer definitions and the concept of cross-linking through use of models. Both curricula align with Next Generation Science Standards (NGSS) around designing solutions to modern problems and carrying out investigations. Additionally, the experiment is ideal for safe, remote-learning instruction. Overarching connections between science and society are highlighted through the global plastics problem, and potential solutions are presented using the green chemistry principles of renewable feedstocks, design for degradation, and less hazardous chemical synthesis.



KEYWORDS: *Elementary/Middle School Science, High School/Introductory Chemistry, Curriculum, Collaborative/Cooperative Learning, Inquiry-Based/Discovery Learning, Hand-On Learning/Manipulatives, Green Chemistry, Polymer Chemistry, Materials Science*

INTRODUCTION

Petroleum-based plastics and their negative effects on the environment are the focus of an increasing volume of scientific research.[1,2] In particular, the impact of plastic products on marine life has garnered much media and public interest.[3] Over 100,000 marine mammal deaths per year were recorded during the 1980s due to entanglement in plastic nets and lines and ingestion.[4] Studies have shown that ingestion of plastic by sea birds, sea mammals, and fish leads to wounds, blocked airways and digestive tracks, drowning, the inability to feed offspring, and impaired reproduction.[5] Media images of the harm plastics cause to ocean life has elevated the awareness of these problems to people of all ages. While plastics have these negative attributes, their wide range of properties and applications are seemingly indispensable to modern society, and their presence occupies all sectors of life.

One obvious daily convenience of plastic is through single-use polyethylene terephthalate (PETE) water bottles. The picture of a PETE bottle discarded on a beach or along the road has become synonymous with the face of consumer waste. Many programs, such as water bottle filling stations and reusable bottles, attempt to offer alternative, environmentally friendly options for consumers. However, single-use bottles are often the preferred choice for their accessibility while on the go. Further, plastic water bottles are essential during natural disasters and crises where clean potable water is difficult or impossible to access. Given these challenges, research is underway to find more sustainable polymers able to replace fossil-fuel-derived commercial products.[6]

One company, Skipping Rocks Laboratory, is selling sustainably sourced packaging, including sauce sachets and

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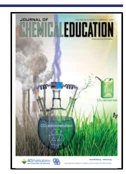

edible water pods, made from brown algae.[7] These water pods gained international attention for their use in the London Marathon in 2019 where they were reported to prevent the distribution and use of 200,000 plastic water bottles.[8] The pods, made from alginate derivatives, are edible, can biodegrade within months, and bypass the problems of petroleum-based plastics, namely, the use of a depleting resource and persistence in the environment. Their products, marketed under the name "NotPLA", have the potential to offer a quick, accessible solution for consumers for quenching their thirst while minimizing the environmental impact. Herein, we describe a novel set of curricula based on these commercial innovations that are designed to introduce grade-appropriate science standards through the synthesis of edible water pods and their food-safe applications.

■ BACKGROUND

Sodium alginate is a naturally occurring, food-safe chemical that is derived from brown algae.[9] Sodium alginate is a linear, anionic polysaccharide composed of two forms of 1,4-linked hexuronic acid residues, guluronate (G) and mannuronate (M), arranged in blocks of repeating GG and MM blocks or mixed M and G blocks, depending on the source (Figure 1).[10]

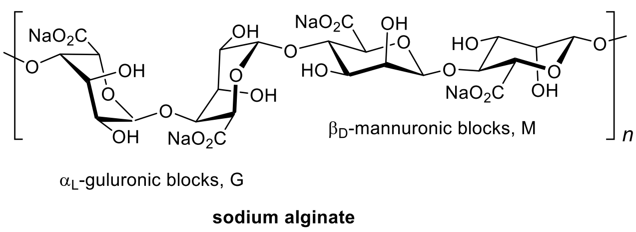

Figure 1. Structure of sodium alginate with pairs of alternating guluronate and mannuronate blocks of disaccharides.

When sodium alginate is reacted with calcium lactate, the calcium ions exchange with the sodium ions. Specifically, calcium cation interactions between guluronate blocks from different alginate strands form a cross-linked network (Scheme 1).[11] The resulting hydrogel structure encapsulates the liquid used to prepare the solutions. Commercially, sodium alginate is a common food additive in dairy products and dressings as an emulsifier, thickener, and stabilizer, and it was sensationalized in the culinary world for its ability to spherify liquids. This phenomenon was popularized by cooking shows such as Netflix's *Sugar Rush* where "avocado toast" cake is topped with an "egg yolk" made from pineapple curd that was spherified by sodium alginate and calcium lactate.[12]

Alginate derivatives have found use in biomedical applications as well. For example, alginate-based microcapsules were tested for use as encapsulation devices for pancreatic islets in a transplant's body and were shown to prevent rejection in patients with severe diabetes who need the life-saving surgery.[13] Bandages made from a composite of alginate and zinc oxide were found to be excellent for healing wounds.[14] The alginate's hydrogel swelling properties promote removal of secreted fluids from the skin to prevent infection, and the zinc oxide improves the antimicrobial properties of the bandage. The numerous and varied applications of alginate-based products offer opportunities to maximize student engagement throughout the lessons.

Experiments capitalizing on alginate's interesting properties can be found in the literature for students in middle school,[15−19] for students at the high school/college level,[20−23] and for outreach.[24] These references illustrate calcium alginate polymers prepared using several different methods, including making beads,[17,20] "spaghetti,"[18] "worms,"[16] and "slime,"[24] as well as by making alginate-chitosan[22] and alginate-polyacrylamide[23] combination polymers. In all cases, with the exception of Boyd's recent publication,[24] calcium chloride was used as the calcium ion source for the alginate gels. Herein we report the use of food-safe calcium lactate as the source of calcium ions enhancing the safety and expanding the options for exploration. Inspiration for this curricula and the abbreviated activity published for the American Society's *Chemists Celebrate Earth Week*,[19] was derived from Beyond Benign's open-access outreach activity titled, "Ocean Plastics".[25] On the basis of our studies, direct comparison of capsules prepared from calcium chloride versus calcium lactate demonstrated the latter to generate capsules of equal to higher quality. In addition, the experiment is suitable for use as a safe, at-home learning activity and proved useful during COVID-19 pandemic restrictions. The food-safe reactants, equipment, and environment offered an extension to the exploration of juices in place of water and allowed students to consume their products.

■ EXPERIMENT DESIGN

Overview of Curricula

Food-grade calcium lactate and sodium alginate used in the experiments can be purchased online through Amazon, Walmart, or food specialty stores. Both the middle and high

Scheme 1. Reaction of Sodium Alginate Guluronate Blocks with Calcium Lactate Forming Cross-Linked Calcium Alginate

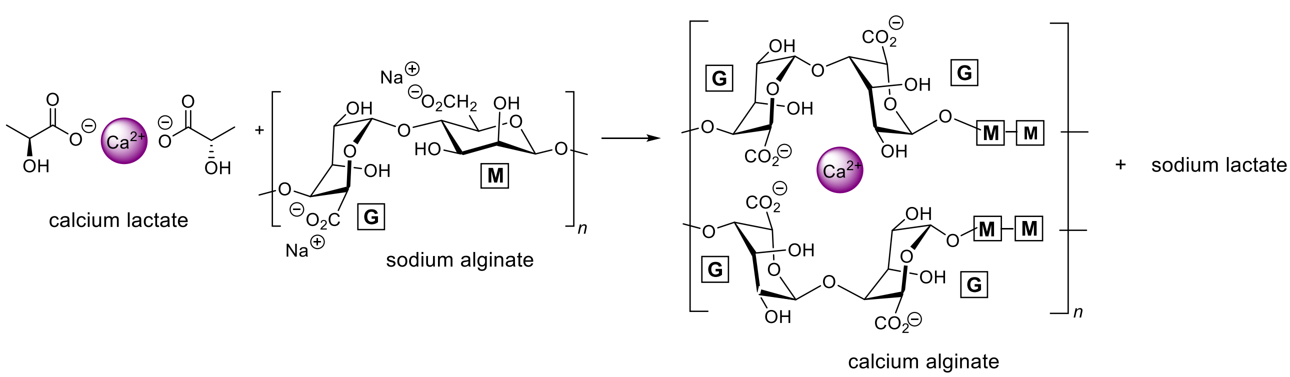

Figure 2. (A) Teaspoon of green-dyed sodium alginate solution placed in the calcium lactate solution. (B) Dropping the forming capsule into the calcium lactate solution. (C) Calcium alginate capsules after removal from the calcium lactate solution.

school lessons include multiple activities of varying difficulty, length, and material requirements. Teachers can select activities relevant to their classes to shorten the curricula as needed without significantly altering the instructional focus. Middle school lesson plans are provided for 5−7 50 min class periods: (a) 2−3 days of introductory activities, (b) 1−2 days for the preparation of capsules, and (c) 2 days for the guided-inquiry project. The high school experiment includes classroom materials for 4−5 50 min class periods. Two days are dedicated to the preparation of the alginate capsules and study of group 2 cations, and the remaining class periods are allotted for the guided-inquiry project. Even though food-safe chemicals were employed for the calcium alginate capsule synthesis in all environments, consumption was only implemented in nonlaboratory settings.

Middle School Experiments

The middle school curriculum was designed to meet the following Next Generation Science Standards (NGSS).[26]

- MS-PS1-1: Develop models to describe the atomic composition of simple molecules and extended structures.
- MS-PS1-2: Analyze and interpret data on the properties of substances before and after the substances interact to determine if a chemical reaction has occurred.
- MS-PS1-3: Gather and make sense of information to describe that synthetic materials come from natural resources and impact society.
- MS-ETS1-1: Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.
- MS-ETS1-2: Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.
- MS-ETS1-3: Analyze data from tests to determine similarities and differences among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success.

To introduce students to polymers and nonrenewable versus renewable resources, several activities and resources are outlined for teachers. A printable "renewable versus nonrenewable resource" card sort game begins the lessons followed by an activity where students compete in groups to build spaghetti noodle "ladders", wherein some groups have finite materials and others have depleting ones, thus illustrating the benefit of renewable resources. Once it is established that petroleum oil, the precursor to synthetic plastics, is a nonrenewable resource, students take an inventory of all the plastic items in their classroom, noting the varied properties and appearance of the products. Finally, to introduce the concepts of polymers before starting the laboratory exercises, students use a ball of yarn tangled to varying degrees to illustrate polymers and cross-linking.

In the first laboratory exercise, students prepare calcium alginate capsules to explore their properties. Working in groups, they prepare solutions of sodium alginate and calcium lactate, using a blender to mix the alginate solution. Food dye may be added to the sodium alginate solution for contrast. Capsules are prepared by carefully placing teaspoons of the sodium alginate solution, open side up, beneath the surface of the calcium lactate solution to begin the reaction (Figure 2A). After 5−10 s, the teaspoon is slowly tipped over to allow the forming capsule to fall into the calcium lactate bath (Figure 2B). After, minimally, 10−15 min, the capsules are gently removed from the solution with a spoon or by hand (Figure 2C). The longer the capsules remain in the solution, the firmer the capsules become with additional cross-linking.

Once several capsules are made, students qualitatively observe the capsules and examine both the benefits and drawbacks of these capsules as potential replacements for single-use bottles. In the second experiment, students work in small groups to determine a variable they can test to potentially improve the function or aesthetics of the capsules. Instructor guidance includes results for modifying the reagent concentrations or additives, and reaction setup such as length of time for capsule formation or order of mixing reagents. After planning and executing their inquiry, groups summarize their work and determine as a class which modifications best improved the capsule.

High School Experiments

The high school curriculum was designed to meet the following NGSS standards.[26]

- HS-PS1-2: Construct and revise an explanation for the outcome of a simple chemical reaction based on the outermost electron states of atoms, trends in periodic table, and knowledge of the patterns of chemical properties.
- HS-PS2-6: Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.
- HS-LS2-7: Design, evaluate, and refine a solution for reducing the impacts of human activities on the environment and biodiversity.
- HS-ESS3-4: Evaluate or refine a technological solution that reduces impacts of human activities on natural systems.
- HS-ETS1-1: Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.
- HS-ETS1-2: Design a solution to a complex real-world problem by breaking it down into smaller, more

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J. Chem. Educ. 2022, 99, 1021−1025

manageable problems that can be solved through engineering.

- HS-ETS1-3: Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts.

In the first experiment, students are asked to assume the role of a chemist in a company that has tasked them with finding solutions to the negative environmental impacts of plastics. Students work in groups to synthesize calcium alginate capsules in the same fashion as the middle school curriculum. Next, students explore cation effects and periodic trends by preparing a series of alginate capsules made with magnesium, calcium, and strontium chloride salts. Barium chloride was originally explored but was removed from classroom implementation due to concerns of toxicity and waste handling.[27] Teams then evaluate their results and design an inquiry project based with the aim of improving a property of the capsules. As noted in the Supporting Information, changes in solution concentration, addition of additives like gum arabic or tapioca starch, reverse addition of reagents, and length of time for capsule formation, or method of capsule formation, all provide observable properties to study. After completing their experiment, students summarize their work by creating research posters to share with their classmates in a gallery walk.

■ HAZARDS

Students should wear proper lab attire, including goggles and gloves, when preparing the capsules in a laboratory setting. If laboratory equipment is used, the capsules should not be consumed. Sodium alginate and calcium lactate may both be purchased as food grade, and strictly, kitchen equipment should be used to prepare the capsules if they are to be eaten. Food-grade calcium chloride and magnesium chloride are commercially available but were not used by the authors. Calcium lactate is a nonhazardous chemical, and sodium alginate has a possibility for food allergies. Capsules made with magnesium, calcium, or strontium chloride should not be consumed. Magnesium chloride is considered nonhazardous. Calcium and strontium chlorides are harmful if swallowed and can cause eye irritation or damage. Hands should be washed thoroughly before and after experimentation.

■ CLASSROOM IMPLEMENTATION AND ACTIVITIES

The middle school curriculum was not formally implemented in a regular academic year classroom due to the pandemic. However, prototype experiments were run in a middle school science summer camp to determine the feasibility of extending the curriculum to middle school grades. During the summer camp, students were observed to be highly engaged with the experiment and enjoyed learning about plastics through an edible experiment. It was noted that during the experiment students needed a significant amount of guidance during the guided-inquiry portion of the project. This information informed modifications to the final curriculum design.

The high school curriculum was implemented at varying degrees in an AP Chemistry class of 15, an AP Environmental Science class of 14, and a Planet Earth elective class of 19. It was also incorporated into a virtual high school teacher workshop during the summer of 2020 and evaluated by 14 Minnesota high school teachers.[28] The three different high school classes received varying levels of introduction commensurate with course learning outcomes before experimentation. All three classes completed the preparation of capsules with aqueous and juice solutions. Food-safe equipment and classrooms were used so students could consume the capsules. Across all three classes, high levels of interest and engagement were observed during the experiment. Students were eager to ask questions, try new combinations of juices, and began informally assessing the viability of the capsules as commercial replacements for single-use water bottles. The AP Chemistry class completed the exploration of the group 2 cation salts. Students observed that capsules formed with calcium chloride (as expected) and strontium salts but did not form with the magnesium chloride. In the research lab, capsules readily formed with barium chloride (see Supporting Information).

■ CONCLUSION

Curricula were designed at the middle and high school levels to introduce the topics of green chemistry and polymer science through exploring the properties of edible water capsules as a replacement for single-use water bottles. These curricula are unique because of their food-safe preparation and focus on the environmental challenges faced by society's dependence on single-use plastics. With the exception of the group 2 cation study, the experiment can be used as a safe at-home/remote-learning assignment. These types of learning activities are particularly needed during times such as those experienced during the COVID-19 pandemic of 2020−2021. In addition, the versatility of the experiment makes it suitable for adoption in an environmental science course, in a food science course, or as an outreach activity.

Detailed teacher instructions provide robust guidance and resources for implementation and success in the classroom. Both levels of curricula highlight inquiry-based learning, which guides students to become the bearers of knowledge in the classroom, while applying the following NGSS scientific practices of (a) planning and carrying out investigations; (b) analyzing and interpreting data; (c) constructing explanations and designing solutions; (d) and obtaining, evaluating, and communicating information.[26] The accompanying materials aid teachers in providing context through bringing awareness to plastics in the environment, and efforts to design more sustainable polymers through the principles of green chemistry.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.1c00905.

Middle school teacher handout, middle school experiment handout, high school teacher handout, and high school student handout (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

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